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# **CHEMICAL ENGINEERING EDUCATION**

APRIL 1966



**FIRST AID**

to Ailing Thermodynamics

# *The Prentice-Hall International Series in the Physical and Chemical Engineering Sciences*

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To the question "What is engineering?" there are a variety of answers given today. Some are helpful, many are confused, a few border on nonsense. Their variegation is impressive, their capacity for mutual contradiction startling. But within the broad range of ideas about engineering there is wide agreement that design—itsself a subject of diversified definition—is a central engineering function and an earmark of the field. It is heartening, therefore, to see a renaissance of process design courses in chemical engineering curricula. The significantly creative efforts in process design pedagogy at McMaster University, M.I.T., Dartmouth, and Michigan, to name a few, promise a bright future for the teaching of design to chemical engineering undergraduates, graduate students, and industrial practitioners.

Process design is as complex as it is important, and to strive for it to yield increasingly optimum plants is to move toward complexity and difficulty that are orders of magnitude greater. In an engineering world where the system seems to be a new discovery in mechanical and electrical realms, the chemical design engineer is an old and calloused hand at dealing with the super system: a chemical manufacturing process that is a linkage of components each of which itself may be a quite sophisticated system. It is appropriate, then, that process design become an unparalleled illustration of splendid systems engineering. The challenge that it do so is matched by a remarkable convergence of favorable conditions: necessary knowledge was never more plentiful, technique never more advanced, computation never more facile, the incentive never stronger.

CHEM ENG ED commends to its readers the significant articles on process design pedagogy carried in this issue and in the preceding one. Others will follow from time to time. Watch for them.

## CHEMICAL ENGINEERING EDUCATION

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# FIRST AID to Ailing Thermodynamics

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Engineering educators stand accused by those investigating the drop in engineering enrollment, of practices that tend to discourage students (2). It appears that there may be just basis for the accusation, particularly apropos of some of the literature with which students are forced to contend.

There is a literary form called the objective correlative. It was used extensively by T. S. Eliot. It has been likened to beefsteak that a burglar carries to divert the watchdog while he robs the safe (3). Mr. Eliot's poetry abounds in this sort of thing; the casual reader gets something—the beefsteak—but it takes real digging to find the underlying idea—the contents of the safe. Eliot must have felt a little sorry for his readers, because he later published footnotes to trace some of his ideas. His good friend, Ezra Pound, on the contrary, felt that it wasn't sporting to put in any footnotes at all.

Even some of the scientific disciplines are producing technical literature that resembles the objective correlative in the confusion it offers the reader. (Nicholas Vanserg's pieces "Mathmanship" and "How to Write Geologese" are entertaining commentaries on publications in two fields (6, 7).) Engineering has not been a major offender in this respect, although examples of misleading prose and illogical terminology can be found in our literature (1, 5). An important instance occurs in the subject of thermodynamics. It is the purpose of this article to propose reforms in the subject; to rearrange the concepts into forms that are more logical under modern conditions; to alter some definitions and conventions in the interest of clarity; and to propose a unifying treatment that can be presented immediately to beginning scholars.

If this objective is to be successful, a certain amount of re-education of faculty

members and research workers will be necessary in advance of its introduction to students in the classroom. It should be emphasized at the outset that these proposals represent some changes in point of view, but they are in every respect algebraically compatible with the more traditional treatment. These changes, evolved from experience with the difficulties that learners have with the subject, were acceptable to those students who were honestly trying to get the picture.

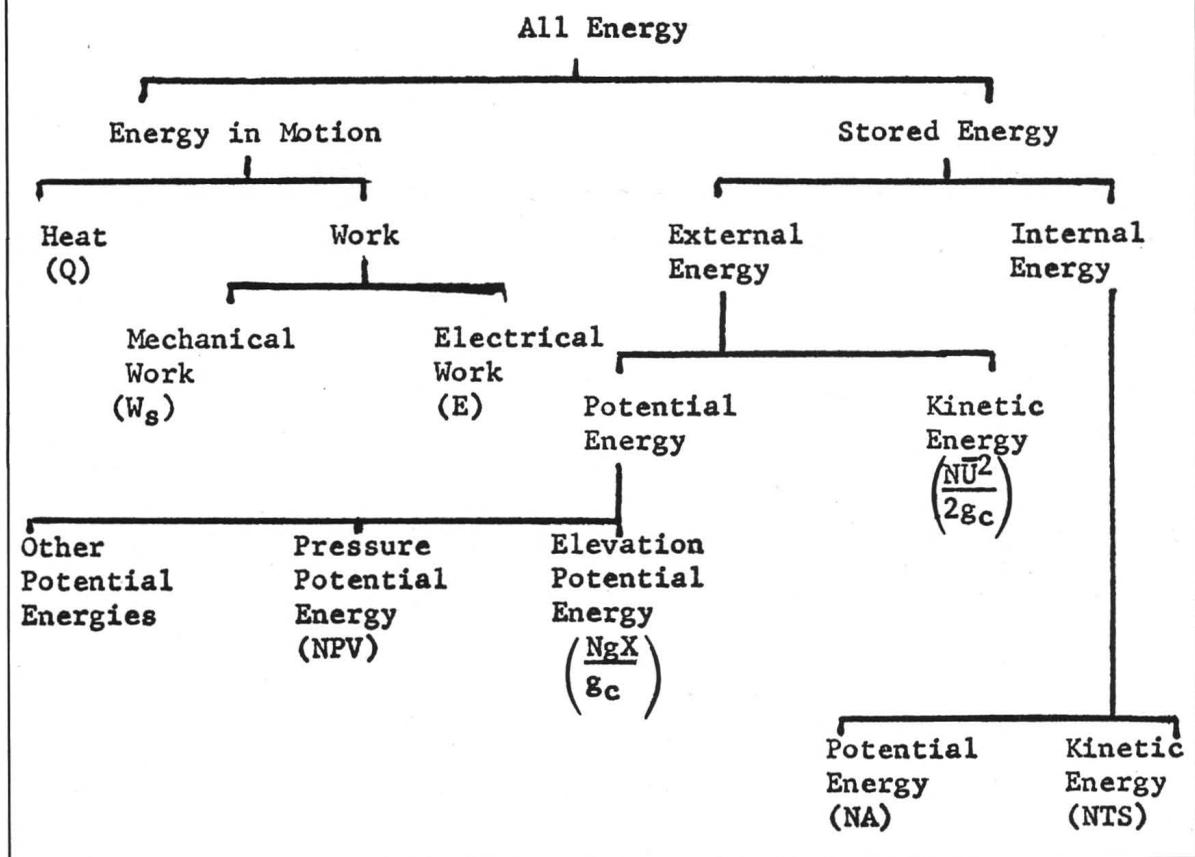
## Improving the Terminology

A little investigation will reveal a number of examples of confusing nomenclature in thermodynamics. It is almost as if the terminology had not been brought up to date for 40 years. Surely it is time for a reappraisal in the educational methods that are needed today.

We may start with the word thermodynamics itself, which means literally "heat in motion," although other kinds of energy transformation are just as important to the subject as heat. A better term would be *energetics*. It is really redundant to say *thermodynamics* because any proper definition of *heat* must include the idea that it is energy in motion. *Heat*, *work*, and *electricity* are all — by definition — manifestations of energy in motion. Unlike *stored energy*, they are not associated with any particular mass of material. They may flow across the boundaries of a system and they may flow through the interior. They are not point functions. The quantity of energy transferred across the boundaries of a system as heat, work, or electricity depends upon the path as well as upon the initial and final values of state conditions such as *temperature*, *pressure*, *volume*, and *voltage*.

The terms *thermostatics*, *stored heat*, *heat content*, *heat capacity*, *stored work*, and *stored electricity* are misnomers. They conflict with the definitions; they confuse students. We must stop using them if we are to have a truly logical body of knowledge. The idea of dividing all energy first

TABLE 1  
THE DICHOTOMY OF ENERGY



into two classes of *energy in motion* and *stored energy* is basic to the understanding of the subject, but we should not allow the idea to be undermined by the use of unprecise and contradictory terms.

Stored energy should be represented by a number of names corresponding to all the commonly recognized classifications. It is worth noting that the classification is complex. The early workers appear to have been afraid that some little understood kind of energy might be left out. As a result they organized a *dichotomy of energy*. This is outlined in Table I. Notice that the subdivisions are always made by dividing into two classes—those that do and those that do not meet some criterion. Thus *stored energy* is divided into *external energy* and *internal energy*. At the next level both of these are divided into *kinetic energy* and

*potential energy*. Now there are clearly several kinds of potential energies on the external side and two of these are shown—but one must remember that in certain special kinds of problems *magnetic potential energy*, *surface potential energy*, or other kinds must be included.

All stored energy terms are associated with a mass of material. They are point functions; differences in their values associated with a change of state of the system are determined solely by the initial and final conditions and are independent of the path.

Certain common energy terms have been left out of Table I deliberately: *non-flow work*, *internal energy*, *enthalpy*, and *Gibbs free energy*. Some of these have their uses, but none of them should be taught to students at first. The reason for this is

that each of these terms represents an arbitrary combination of simpler terms, as can be seen from the following equations

$$dW = dW_s + d(PV) \quad (1)$$

$$dU = dA + d(TS) \quad (2)$$

$$dH = dU + d(PV) \quad (3)$$

$$dF = dH - d(TS) \quad (4)$$

where  $A$  = Helmholtz free energy,  $F$  = Gibbs free energy,  $H$  = enthalpy,  $P$  = absolute pressure,  $S$  = entropy,  $T$  = absolute temperature.  $U$  = internal energy,  $V$  = volume,  $W$  = non-flow work, and  $W_s$  = shaft work.

### A Canon for the First Law

The first law of thermodynamics is an energy balance. Unfortunately, the literature is full of different statements of this law. There seems to be no clearly recognized, generally agreed upon, form that could always be used as a starting point. Students need such a statement which they can use to avoid the possibility of leaving out some energy terms that are important to their problem. If they were to be given a universal formulation or *canon* to begin every problem, and it were clearly stated that subsequent manipulations apply only to a particular situation, it would be easier to break the habit of formula snatching which many of them attempt to practice.

In view of the fact that the first division employed in the dichotomy of energy, Table I, is that between energy in motion and stored energy, it is suggested that an equality be used to relate the two kinds of quantities in a system. As a matter of fact, some textbooks do this by putting heat, work, and electricity on the left side and all stored energy terms on the right side. On the stored energy side it is recommended that one term be provided for each kind of energy, all combination terms being avoided. It is also recommended that the standard form of the energy balance be written with differentials, since deltas and integral signs raise questions about datum levels, the initial and final states, or constants of integration—all matters having to do with a particular problem. Beginning engineering students should be able to perform the necessary integrations.

With these recommendations in mind a *canonical statement of the first law* can be formulated as follows:

$$dQ - dW_s - dE = dA + d(TS) + d(PV) + d\left(\frac{NgX}{g_c}\right) + d\left(\frac{N\bar{U}^2}{2g_c}\right) \quad (5)$$

where  $E$  = electricity,  $g$  = acceleration of gravity,  $g_c$  = gravitational conversion factor,  $N$  = mass,  $Q$  = heat,  $\bar{U}$  = velocity, and  $X$  = absolute elevation.

### What Is Work?

The so-called work terms in the energy balance do not always satisfy the criterion of representing energy in motion. Lectures intended to establish the principle that heat, work, and electricity are always energy in motion are weakened by the algebra in many textbooks. That which is usually called non-flow work ( $W$ ) in a batch process is one such instance. This can be shown by algebraic manipulation to be:

$$W = W_s + \Delta(PV) \quad (6)$$

The *shaft work* ( $W_s$ ) clearly satisfies the definition of work; i.e., it is energy in motion. It requires a machine with a rotating shaft or a moving piston rod. The so-called *flow work* or *flowing energy term*,  $\Delta(PV)$ , is a different matter. It represents stored energy, for it is a point function. For this reason the terms flow work and flow energy also should be avoided.

An excellent exercise to give students early in their course work involves them in a pressure-volume graph. They are asked to choose points on the graph representing arbitrary initial and final states and to draw two arbitrary paths between these points with a French curve. They are then asked to evaluate graphically for each path the quantity

$$\int_1^2 PdV + \int_1^2 VdP$$

and to compare the two values with the value of the function  $P_2V_2 - P_1V_1$ . Since all of the expressions give the same result, the students can see readily that  $\Delta(PV)$  is a point function and that the individual integrals are *not* point functions, for they do depend upon the path.

Another approach is to write  $\Delta(PV)$  as  $N \Delta(P/\rho)$ . The mass  $N$  is the capacity factor and  $P/\rho$  is the intensity factor of the energy term. The later is readily recognizable as the pressure head in Bernoulli's equation. Therefore,  $\Delta(PV)$  is really *pressure potential energy*. For example: putting work into a compressor that delivers compressed air to a pressure tank at the corner service station is analogous to putting work into a pump that supplies water to an elevated tank at the water works. Both the air in the pressure tank and the water in the elevated tank possess stored potential energy. In order to differentiate them  $Ng \Delta X/g_c$  should be called *elevation potential energy* and  $\Delta(PV)$  should be called *pressure potential energy*.

Thus  $W$  turns out to be a mixture of work and stored energy, and it should no longer be referred to as work. Some books try to make  $W$  look like pure work by attempting to show that  $\Delta(PV)$  is work. The explanation usually goes something like this: "The gas that goes into the process enclosure is pushed in by the gas that follows it, and the gas that leaves the enclosure pushes back the atmospheric air." This is very confusing to students because they cannot visualize other gas or air as being the same as the face of a piston. They also find it hard to follow an imaginary boundary that shifts as the gas passes through it. The educational advantage of the new point of view should be clear, for it does not require such explanation.

#### The Trouble With Enthalpy

Kammerling Onnes (4) invented the term *enthalpy* as a substitute for such terms as *stored heat* and *heat content*. Although it was a worthwhile advance, it still gives trouble. Some students tend to equate enthalpy with heat without regard to the effects of other terms in the energy balance. Of course enthalpy is a hybrid concept consisting of part internal energy and part external pressure potential energy. Such a mixture is quite illogical though convenient in many practical problems. A logical alternative would be to discard enthalpy and return to internal energy. Unfortunately, this is not likely to come to pass; for the literature is full of tables and graphs of enthalpy, and there are comparatively few

data in the form of internal energy.

The progress of understanding would be aided, however, if the terms *heat capacity* and *latent heat* were abandoned. These terms provide a misleading connection between heat and enthalpy that should be discouraged. Students will get along with much less trouble with the terms *enthalpy capacity* instead of "heat capacity at constant pressure," *internal energy capacity* instead of "heat capacity at constant volume," *latent enthalpy* instead of "latent heat at constant pressure," and *latent internal energy* instead of "latent heat at constant volume." At first these new names seem cumbersome to old timers, but this is not the case with beginning learners.

#### Extending the First Law of Energetics

In Table I and Equation 5 internal energy is divided into internal potential energy and internal kinetic energy. This is done arbitrarily, calling  $TS$  the *internal kinetic energy* and  $A$  (the Helmholtz free energy) the *internal potential energy*. In view of the statistical difficulties of dealing with the interactions of all of the molecules and sub-atomic particles this may seem to be questionable. However, in view of the relationship of Equation 2, the fact that there are only two subdivisions under internal energy (no unknown form of energy thus being overlooked), and the convention of a form of the first law that includes no combination terms, it is logical to make such a division.

#### Handling Irreversible Processes

For a reversible process,

$$dQ_{\text{reversible}} = Tds \quad (7)$$

$$dW_{\text{reversible}} = -VdP \quad (8)$$

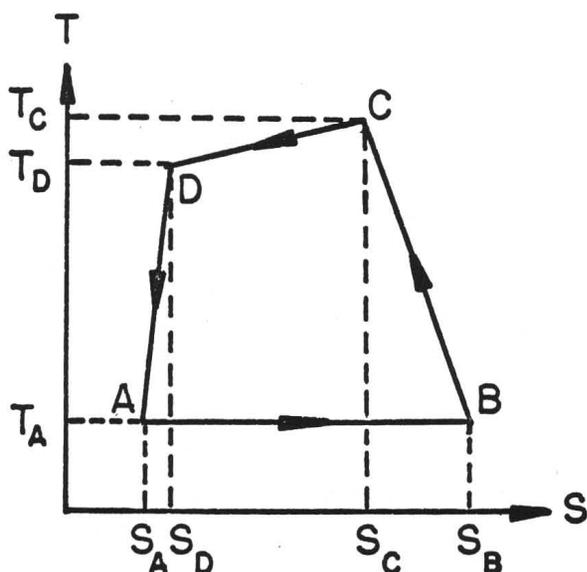
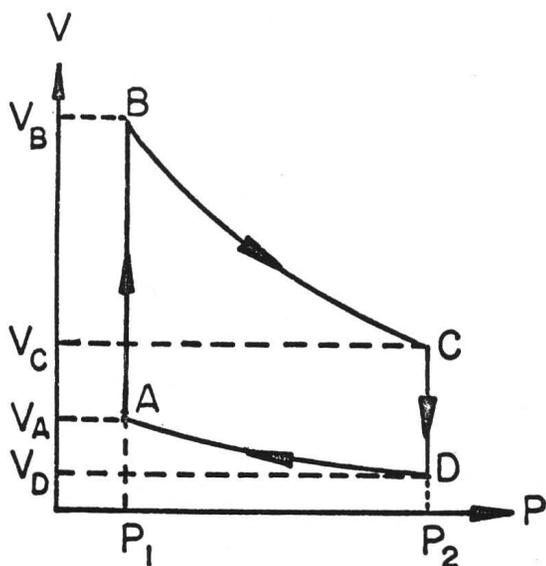
The canonical statement of the energy balance for such a process results from the substitution of Equations 7 and 8 into Equation 5 (with electricity assumed to be zero):

$$TdS + VdP = dA + (TdS + SdT) + (VdP + PdV) + \frac{Ng}{g_c} dX + \frac{N}{g_c} d\left(\frac{\bar{U}^2}{2}\right) \quad (9)$$

For the reversible case the like terms on both sides of the equation may be cancelled. *But wait! All actual processes are irrevers-*

# Table II

## An irreversible ideal-gas compressor



$P_1 = 14.7 \text{ psia}$   
 $P_2 = 85.0 \text{ psia}$   
 $V_A = 0.0255 \text{ ft}^3$   
 $V_B = 0.850 \text{ ft}^3$   
 $V_C = 0.2245 \text{ ft}^3$   
 $V_D = 0.00675 \text{ ft}^3$   
 $C_P = 7.00 \text{ Btu}/(\text{Lb mole} \cdot ^\circ\text{R})$   
 $C_V = 5.01 \text{ Btu}/(\text{Lb mole} \cdot ^\circ\text{R})$   
 $K = 1.400$   
 $n = 1.318$

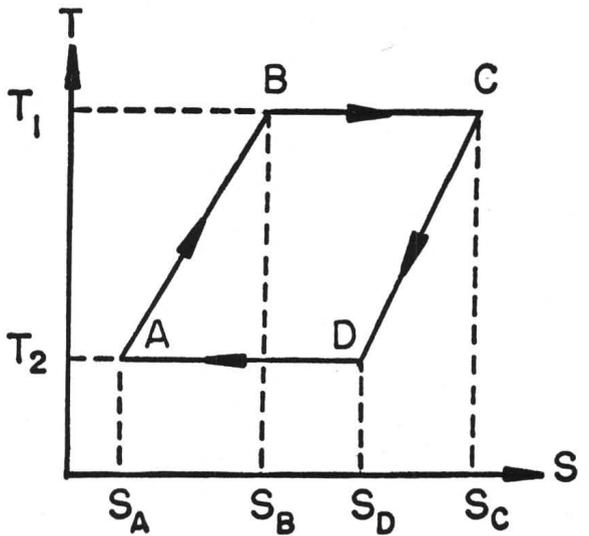
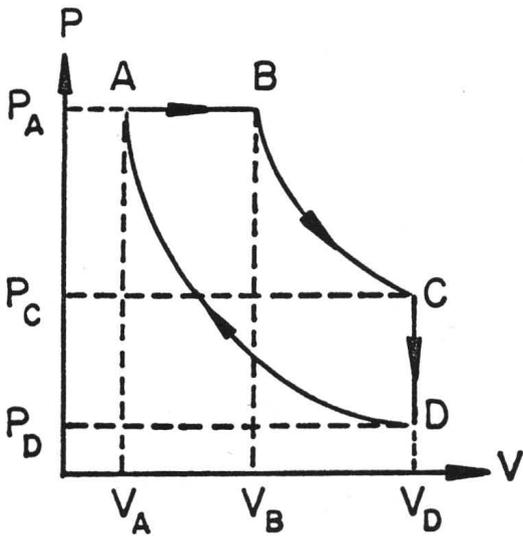
$T_A = T_B = 530. \text{ }^\circ\text{R}$   
 $T_C = 808. \text{ }^\circ\text{R}$   
 $T_D = 700. \text{ }^\circ\text{R}$   
 $S_A = + 0.040 \times 10^{-3} \text{ Btu}/^\circ\text{R}$   
 $S_B = + 3.91 \times 10^{-3}$   
 $S_C = + 2.377 \times 10^{-3}$   
 $S_D = + 0.157 \times 10^{-3}$   
 $N_A = N_D = 0.000,0764 \text{ Lb mole}$   
 $N_B = N_C = 0.00220 \text{ Lb mole}$

### Energies in Btu

Function	A B	B C	C D	D A	A B C D
Q	0.00	- 0.76	- 1.67	+ 0.11	- 2.32
Ws	0.00	- 5.05	0.00	+ 0.15	- 4.90
W	+ 2.24	- 3.82	- 3.43	+ 0.11	- 4.90
$\Delta(PV)$	+ 2.24	+ 1.23	- 3.43	- 0.04	0.00
$\Delta U$	0.00	+ 3.05	- 0.47	0.00	+ 2.58
$\Delta H$	+ 2.24	+ 4.28	- 3.90	- 0.04	+ 2.58
$T \Delta S$	+ 1.86	- 0.76	- 1.67	- 0.09	- 0.66
$\Delta(TS)$	+ 0.004	0.00	- 0.004	0.00	0.00
$\Delta A$	- 0.004	+ 3.05	- 0.466	0.00	+ 2.58
$\Delta F$	+ 2.236	+ 4.28	- 3.896	- 0.04	+ 2.58
$\Delta S \times 10^3$	+ 3.510	- 1.155	- 2.22	- 0.117	0.00

Table III

A reversible diesel engine cycle



$V_A = 2.46$  liters  
 $V_B = 4.10$  liters  
 $V_D = 24.6$  liters  
 $P_A = 10.0$  atmos  
 $P_C = 1.670$  atmos  
 $P_D = 1.000$  atmos

$T_1 = 500.^\circ\text{K}$   
 $T_2 = 300.^\circ\text{K}$   
 $S_A = -4.11$  cal./ $^\circ\text{K}$   
 $S_B = -0.53$  cal./ $^\circ\text{K}$   
 $S_C = +3.03$  cal./ $^\circ\text{K}$   
 $S_D = +0.46$  cal./ $^\circ\text{K}$

Energies in Calories

Function	AB	BC	CD	DA	ABCD
Q	+1,400.	+1,780.	-1,001.	-1,375.	+ 804.
$W_s$	0.	+1,780.	+ 399.	-1,375.	+ 804.
W	+ 399.	+1,780.	0.	-1,375.	+ 804.
$\Delta(PV)$	+ 399.	0.	- 399.	0.	0.
$\Delta U$	+1,003.	0.	-1,003	0.	0.
$\Delta H$	+1,400.	0.	-1,400.	0.	0.
$T \Delta S$	+1,400	+1,780.	-1,001.	-1,375.	+ 804.
$\Delta F$	0.	-1,780.	- 399.	+1,375.	- 804.
$\Delta S$	+ 3.58	+ 3.56	- 2.57	- 4.57	0.

ible. The right side of the equation represents *stored energy*; all of the functions on the right side are point functions. The left side of the equation represents *energy in motion*, namely heat and work. If the work goes into the enclosure and heat comes out, irreversibilities and friction increase both heat and work beyond the limiting case. Now either the  $Tds$  or the  $VdP$  term on the left side will have to be integrated (graphically or formally) over the actual path. It is not necessary to integrate both terms, for the energy balance can be solved for the second term on the left side. The right side can be evaluated with the aid of the second law.

Many textbooks seem to place too much emphasis on reversible cases. In engineering the greatest emphasis should be on the irreversible. A useful technique in teaching students is to represent cycles, reversible or irreversible, on both  $P$ - $V$  and  $T$ - $S$  plots. The various steps of the cycle and the complete cycle should be investigated completely. All of the terms and their components should be calculated, and all of the numbers should be tested in the light of the first and second laws and the various defining equations to locate errors and reinforce understanding. A few such exercises are the equivalent of a much larger number of discrete one-step, one-question, one-answer problems. Tables II and III illustrate this technique. Students to whom algebraic equations are somewhat unreal achieve quicker understanding when they are required to substitute numbers, and the inevitable mistakes that crop up are illuminated immediately.

#### What Sign Should the Work Term Have?

The usual convention is that heat flowing into the system is positive and work flowing out of the system is also positive. This appears so illogical that teachers should keep their eyes open for a clue showing which of these signs can be changed the more reasonably. Evidence appears very quickly. Inasmuch as work input, like heat inflow, is associated with an increase in the value of such thermodynamic properties of the system as enthalpy and free energy, its sign should be positive for consistency with the general convention. If it were, both heat and work would be positive for flow into

the system and negative for flow out of the system—a much more satisfactory situation.

#### Conclusion

Thermodynamics (energetics, that is) is ailing—or, speaking more precisely, its pedagogy is. The illness is neither organic nor incurable, but it is debilitating and it should be checked. This critique has suggested some therapeutic measures. Will they be effective? Can they help students understand one of the foundation subjects of their engineering education? The experience of one instructor is affirmative, but in the end each must try them himself to find out.

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#### NOMENCLATURE

- $A$  = Helmholtz free energy  
 $E$  = Electricity  
 $F$  = Gibbs free energy  
 $g$  = Acceleration of gravity  
 $g_c$  = Gravitational conversion factor  
 $H$  = Enthalpy  
 $N$  = Mass  
 $P$  = Absolute pressure  
 $Q$  = Heat  
 $S$  = Entropy  
 $T$  = Absolute temperature  
 $U$  = Internal energy  
 $\bar{U}$  = Velocity  
 $V$  = Volume  
 $W$  = Non-flow work  
 $W_s$  = Shaft work  
 $X$  = Absolute elevation  
 $\rho$  = Density



# Shri Jayant Saraiya ENGINEER

*Lloyd Berg*

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At 9:30 P.M. on a cold, windy night in January, 1966, the telephone rang at the Sixth Street home of Mr. and Mrs. Jayant Saraiya in Sinclair, Wyoming. Jay, who was watching TV, got up and answered. "Jay? This is Sam at the plant. The temperature on the regenerator has been slowly dropping all evening. Thought I better tell you." "Thanks," said Jay. "I'll be right over." He hung up, walked over to the kitchen window where he could see an outside thermometer which indicated a cool seven below zero, and proceeded to don a ski parka, boots, and leather cap with ear flaps. "I'll be at the plant for awhile; don't wait up for me," he called to his wife. He stepped into his 1963 Falcon, and drove the four blocks to the plant. The plant is Sinclair Refining Company's refinery at Sinclair, near Rawlins, Wyoming.

Going directly to the control house, Jay talked with Sam Watkins, the shift supervisor. He studied the temperature, pressure, and throughput logs of the refinery that the recording instruments spewed out steadily. "Sam," Jay said finally, "Let's go down to the blower house and look around." Donning their heavy parkas and caps, they went out into the icy wind and across the refinery yard to a small galvanized iron building which housed the blower for the regenerator. This machine gulps in the enormous quantities of air required to burn the carbon off the catalyst and forces it into the burning vessel, called the regenerator. The blower was screaming at a high pitched roar in its usual manner and at its designed speed. Jay had noted in the control room a reduced air flow from the blower. Now by inspecting the blower equipment carefully, he finally noted that the air intake duct above the roof had built up a ring of ice which was restricting the flow of air to the blower. Pointing this out to Sam, he suggested that Sam call the maintenance foreman and ask him to chip off the ice. "I'm sure that will correct the trouble and I'm going home," he told Sam. "If the temperature doesn't start back up after they finish knocking off the ice, call me."

Just another common incident in the working life of an industrial chemical engineer, with this difference. Jay Saraiya is an Indian national trained as a chemical engineer in the United States who plans to spend his professional career in the U.S. A lack of interest in chemical engineering on the part of U.S. youth and a burgeoning demand has created an opportunity that

foreigners are taking advantage of. Some educators have estimated that we may soon reach the point where one fifth of all chemical engineers being graduated by U.S. engineering schools will be non-citizens.

Jay's experience is typical. Born and raised in Bombay as the son of a moderately wealthy importer, Jay went to the University of Bombay and majored in chemistry and physics. In 1959, by straining the family's financial resources almost to the breaking point, he went to the United States and enrolled as a freshman in chemical engineering at Montana State University. Technical education in India is conducted in English, so language was no handicap. Four years later he was graduated as a B.S. in Chemical Engineering. Immediately upon graduation he was hired by Sinclair. Desperately short of chemical engineers and located in what many Americans consider "Nowheresville," Sinclair and Rawlins welcomed Jay with open arms. Company employees found Jay a comfortable apartment in Rawlins for \$35 per month and the local newspaper ran a feature article on Jay and his history.

Feeling that he would be a happier and more stable employee if he were married, Sinclair encouraged him to take his vacation ahead of schedule to go to India to get his bride. Accordingly, in January Jay married Jayshee Asher, a Bombay girl selected with his family's approval according to the Indian tradition.

Jay and Jayshee returned to the high, barren, wind-swept plains of Wyoming in February. After having spent her entire life in steaming, teeming, tropical Bombay, Rawlins seemed like another planet to Jayshee. But there were compensations. The apartment was warm, comfortable, and convenient—and then there were the stores, particularly the supermarket with its abundance and cleanliness like nothing she had ever experienced in India.

Spring comes late at 6500 feet altitude but it does come eventually. In summer there were trips to the nearby Wind River and Teton mountain ranges and to Yellowstone Park.

In November, their son Monal was born. Now the difference between India and America really became apparent to Jayshee. What with the washer and drier, the canned milk and baby food, the abundance of shots, pills and vitamins, the baby was never sick. A major crisis was narrowly

*(continued on page 51)*

### ABOUT — Skepticism Being Better than Paranoia.

It could be argued that what the world offers to this year's scientific or engineering graduate represents the greatest promise ever held out to his kind as individuals. Arguments on the other side are easier to find and they agitate and stimulate. What historian Richard Hofstadter calls the "paranoid style" is enjoying popularity in the United States. We can build black worries on all sides: Business life is enforced conformity; technology is dominating humanity instead of serving it; government for the people is perishing; and the free intellectual stimulation of the university has succumbed to the scramble for federal grants.

General day-to-day progress usually is stumbling and uneven. Worthy minds are inspired by and aspire to the high peaks of human works. The inclination to match this week's failures against mankind's better achievements—as they stood out against the poorer levels of their times—can bring discouragement and feelings of frustration.

We hear and see evidence that among college students there may be greater than usual discontent with the world. Students are reported discontented over too few opportunities for having a hand in making human society better. This is admirable insofar as the attitude is based on understanding. But viewing a mountain from one position doesn't tell much about how hard it would be to climb the unseen side. Some skepticism and probing to learn just what can be done should be a part of the approach of any technically trained person.

Society is changing and is likely to change with increasing speed. Such elements as business, technology's influence, government, and the university atmosphere all could stand some improvement. But all of these are likely to remain influential elements of society and, if they are to be improved, they will have to have the driving efforts of able people. Therein lie challenges to the worthiest of idealists who want to improve the human lot.

After baccalaureate (at Illinois) and doctoral (at North Carolina) degrees in chemistry, Dr. Richard L. Kenyon became a research chemist with DuPont. During four years of research, a strong interest in people and in professional communication persisted and ultimately led him to join the publications staff of the American Chemical Society. As a field editor of *Chemical and Engineering News* and *Industrial and Engineering Chemistry*, as managing editor of the *Journal of Agriculture and Food Chemistry*, as editor of *C & E N*, as editorial director of ACS's applied journals, and finally as Director of Publications for ACS, he has devoted two extremely fruitful decades to the challenging business of more accurate, more literate, more readable, and more exciting communication in the world of applied chemistry and chemical engineering.

Many of our readers doubtlessly have enjoyed Dr. Kenyon's scholarly, arresting editorials in *C & E N*. The message of a recent one was so timely a piece of mature opinion that we wished to have it respoken from our pages. It is reprinted from the Career Opportunities Supplement of the March 14, 1966, issue of *Chemical and Engineering News*. **CHEM ENG ED** is grateful to the American Chemical Society for permission to reprint it.

The new graduates at all levels of chemistry and chemical engineering probably are, on the average, the best trained ever. The demands for excellent training probably also will be the greatest ever. And not only will demands for high training be the greatest, but demands for breadth also are growing.

There appears to be exciting opportunity for competent, well-trained and educated chemists and chemical engineers far beyond the numbers that will be produced. This is true not only in the highest form of "pure" research, but in applied research, technology, commerce, politics, and a host of other pursuits. Those who want a feeling of contributing to the improvement of society should not turn their backs on what appears to be a slightly tawdry mess in comparison to one's ideal society. There lies a very real challenge.

# Unit Operations to Transport Phenomena

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Engineering as a profession was first identified with weaponry and military works. The demand by the civilian populace for structures primarily designed for commerce and trade led only in the last 250 years to "civil" engineering and the civil engineer, whose job was defined in 1828 in the charter of the Institute of Civil Engineers. Civil engineering was "the art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation and docks for internal intercourse and exchange, and in the construction of ports, harbors, moles, breakwaters and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and the construction and adaptation of machinery, and in the drainage of cities and towns" (2). This early definition of engineering is primarily concerned with construction not design, and with art rather than science. It is because of this latter point, in addition to the very ambitious nature of the definition, that it became necessary to divide the field of engineering. The mechanical engineer came to be identified with "the construction and adaptation of machinery," the naval engineer with the "art of navigation by artificial power," and the sanitary engineer with "the drainage of cities and towns." Once under way, the subdivision of engineering increased as the demands of industry became more specialized.

The chemical engineer did not appear until about 70 years ago. The construction and selection of equipment for chemical plants was once largely in the hands of mechanical engineers who knew some chemistry or chemists who knew some mechanical engineering. As the process industry grew, the problems became more complex and peculiar, until it finally appeared that

there was a need for a distinct branch of engineering to which such problems might be assigned. "In response . . . we have the development of chemical engineering, not as a composite of chemistry and mechanical or civil engineering, but as a separate branch of engineering, the basis of which is those unit operations . . . which, in their proper sequence and coordination, constitute a chemical process as conducted on the industrial scale" (2). The unit operations really became the defining concept for chemical engineering and allowed the chemical engineer to use a systematic approach to the solution of complex industrial problems. The distinction between industrial chemistry and chemical engineering, in fact, is that the former is concerned with individual processes as entities in themselves, whereas the latter focuses attention on the unit operations common to many processes and on the proper grouping of these unit operations to produce a desired product.

In 1915 Arthur D. Little formally defined the unit operations of chemical engineering, and in 1923 the text by Walker, Lewis and McAdams entitled "Principles of Chemical Engineering" appeared. During the period from 1923 until 1960, this work and its two revisions served as models for subsequent chemical engineering text books (1-6).

In the mid 1950's, it became apparent to some chemical engineers that, because of the economic demands, there had to be a departure from the traditional approach of multiple scale-up in the design of chemical plants. Some chemical engineering teachers were finding that "too often the fundamental concepts and laws have been slighted in the haste to teach application. The result has frequently been that a practicing engineer or graduate student, faced with problems for which his empirical training has not prepared him, has first had to learn the fundamental principles of the transport processes before he could proceed" (3). The transport processes underlie the unit operations of chemical engineering, for "the unit operations themselves, although carried out

in a wide variety of equipment types that apparently have nothing in common are, from the point of view of the theory involved, applications of a very few fundamental laws. In fact, these laws are the fundamental laws of physical sciences that underlie practically all technology . . . [They] are: first, the conservation of matter and energy; second, the relations pertaining to the equilibria of physical and chemical processes; and third, the laws governing the rate of change in systems not in equilibrium" (2). The recent innovation, then, is not in recognizing that the unit operations are based on a few fundamental laws but in teaching these laws (particularly those that describe process rates) in a separate course which "should rank along with thermodynamics, mechanics, and electromagnetism as one of the key engineering sciences" (4).

#### What Is Meant by Transport Phenomena?

Courses in transport phenomena consist of the study of the transfer of momentum, energy, and mass. In order to transfer any of these quantities, a non-equilibrium situation must exist. For example, if internal energy is to be transferred, there must be a temperature difference. The temperature difference is the driving force and the quantity which is moved by this temperature difference is called the heat flux. From the observational point of view, a linear relation is postulated between the flux and the driving force in which the coefficient of proportionality is a property of the substance in which the energy transfer is occurring. In the case of heat transfer, the coefficient of proportionality is the thermal conductivity,  $k$ .

The observational or phenomenological approach is not concerned with the mechanism for the transfer of this energy. For the mechanism, the kinetic theory of molecular motion must be considered. From the simplified theory, the kinetic energy of a spherical molecule is directly related to the temperature

$$\frac{1}{2}mu^2 = \frac{3}{2}KT \quad (1)$$

The tendency toward equilibrium of temperature then is a result of the transport of molecules with high kinetic energy to regions where the molecules have low kin-

etic energies and vice-versa. But while a molecule, by its change of location, is transferring kinetic energy, it must at the same time transfer mass,  $m$ , and momentum,  $mu$ . On a microscopic level, the mechanism for the transport of mass, momentum, and energy is fundamentally molecular diffusion.

From the observational point of view, the following laws for the transfer of momentum, energy, and mass under the condition of constant density and heat capacity define the transport properties of viscosity,  $\mu$ , thermal conductivity,  $k$ , and mass diffusivity,  $D_{AB}$ .

$$\tau_{yx} = - \left( \frac{\mu}{\rho} \right) \frac{d(\rho v_x)}{dy} \quad (2)$$

Newton's Law of Viscosity

$$q_y = - \left( \frac{k}{\rho C_p} \right) \frac{d(\rho C_p T)}{dy} \quad (3)$$

Fourier's Law of Heat Conduction

$$j_{A,y} = - D_{AB} \frac{d\rho A}{dy} \quad (4)$$

Fick's First Law of Diffusion

From the simplified kinetic theory, the expressions for transport properties are:

$$\mu = \frac{2}{3\pi^{3/2}} \frac{(mKT)^{1/2}}{d^2} \quad (5)$$

$$k = \frac{1}{d^2} \left( \frac{K^3 T}{\pi^3 m} \right)^{1/2} \quad (6)$$

$$D_{AB} = \frac{2}{3} \left( \frac{K^3}{\pi^3 m_A} \right)^{1/2} \frac{T^{3/2}}{pd_A^2} \quad (7)$$

where  $d$  is the molecular diameter. Experiment agrees with the temperature and pressure dependence of the transport properties as shown in Equations 5-7 and therefore verifies the molecular transport mechanism. This is of engineering value in that for moderate ranges, the temperature and pressure dependence of the transport properties can be predicted.

What other information of engineering value can be obtained from these rate equations? The dimensions of  $\mu/\alpha = \nu$ ,  $D_{AB}$ , and  $k/\rho C_p = \alpha$  are (length)<sup>2</sup>/time.

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**FUNDAMENTALS OF CHEMICAL REACTION ENGINEERING**, by Walter Brotz; translation from German by D. A. Diener and J. A. Weaver; Addison-Wesley Publishing Company, Reading, Mass., 1965. 325 pages. \$15.00.

It is stated in the translators' preface of this book that the book can be used at the senior or first-year-graduate level. Most seniors will in fact find it to be a rather sophisticated mathematical treatment not only of reaction engineering but also of some conventional unit operations as well. Though sophisticated, the mathematics are not beyond that to which current undergraduates are exposed.

Much of the material contained in the first 183 pages is not directly related to reaction engineering and will not be new to a fourth-year student. In the first 68 pages, the reader is taken through stoichiometry and thermodynamics and introduced to chemical kinetics and catalysis, the last two subjects in 24 succinct pages. Primarily these 183 pages contain a wealth of design information about fluidized beds, packed beds, and heat exchangers. Much of this information is very skillfully organized into tables and graphs. The text is short on theory but long on application.

The remaining 231 pages are concerned with various types of reactors and their design. The presentation is good. More emphasis is put on the derivation of the equations here than in the first section and this is as it should be. In keeping with the first part of the book, the heat and mass transfer aspects of reactor design are emphasized. The book should be of value to those wishing to bring themselves up to date on the subject of reaction engineering.

This reviewer attempted to use the book for a fourth-year, one-semester course covering applications of transport theories, including reactor design. The sections covering the conventional unit operations were well-received. Students found the charts

and graphs particularly useful. Most disturbing to them was the lack of problems and a sufficient number of illustrative examples. While the symbols in the text have been properly "Americanized," the formulation of the equations is not always that of the more conventional texts. As a result, the students encountered some difficulty when problems were assigned from other texts. One final point: few undergraduate courses are so broadly based that this book can be used in its entirety. With the present curriculum at the State University of New York at Buffalo this reviewer probably would try to use it again.

For a first printing there are surprisingly few errors. To show that it is not perfect, however, the section on multiphase reactors (pp. 232-246) is singled out. Here signs are lost and notation is poor. For some reason the symbols for the mass transfer coefficients are changed from that introduced earlier (p. 108). Concepts like conversion are introduced for no apparent reason. More importantly, the development of the transfer coefficients on page 235 is at best misleading. Does the author (or do the translators) really mean  $k_{G_1}$  and  $k_{G_1}$  to be the film coefficients pertaining to the case of absorption without chemical reaction? Since no use is ever made of this concept the reader never finds out.



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By analogy with the mass diffusivity,  $D_{AB}$ ,  $\nu$  is called the momentum diffusivity and  $\alpha$  is called the thermal diffusivity. Since these three quantities have the same units, dimensionless numbers can be formed from the ratio of any two of them. For example, the Prandtl number is given as

$$\text{Prandtl number} = \frac{\mu C_p}{k} = \frac{\nu}{\alpha} = \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}}$$

and can be interpreted as a measure of the capacity of a fluid to diffuse momentum as compared with its capacity to diffuse heat. The Prandtl numbers for air, water and mercury are approximately 1.0, 5.0 and 0.01, respectively.

The next question is how do the transport properties fit into the conservation statements for mass, momentum, and energy? The conservation statements must be applicable to all substances and, furthermore, they must be independent of any reference frame. The transport properties serve as parameters in the conservation statements and permit a distinction to be made when the same conservation statement is applied to two different substances. For the latter requirement the conservation statements must be expressed by a mathematics which is also independent of coordinate system. The calculus of vectors and tensors transforms the basic laws from reference frame to reference frame with no change in the fundamental law.

Consider now the application of the three conservation statements to a single one-dimensional, time-dependent system:

$$\frac{\delta}{\delta y} \left( \alpha \frac{\delta T}{\delta y} \right) = \frac{\delta T}{\delta t} \quad (8)$$

Conservation of Energy

$$\frac{\delta}{\delta y} \left( \nu \frac{\delta(\rho v_x)}{\delta y} \right) = \frac{\delta(\rho v_x)}{\delta t} \quad (9)$$

Conservation of Momentum

$$\frac{\delta}{\delta y} \left( D_{AB} \frac{\delta \rho_A}{\delta y} \right) = \frac{\delta \rho_A}{\delta t} \quad (10)$$

Conservation of Chemical Species

These equations are all of the same form. Consequently, under certain conditions, there is an analogy among the conservation statements as well as an analogy among the mechanisms for transfer. This analogy can be very useful in the solution of certain engineering problems. For example, the transfer of momentum in a wire-coating operation where the coating is applied by pulling the wire through a die is exactly analogous to the flux of heat in the insulation on a steam pipe. Information about the first system can be inferred by a study of the second, since the systems are analogous.

### Methodology of Transport Phenomena

In order to justify the statement made earlier that a course in the transport process should be ranked along with thermodynamics, let us compare the derivations of the Bernoulli equation.

In most unit operations texts, the derivation is limited to a steady flow system consisting of a pump which takes an incompressible liquid at one elevation and raises it to a second elevation at mass flow rate  $w$ . A pound of liquid at the entrance has a potential energy  $gh_1$ , a kinetic energy  $\langle v_1 \rangle^2 / \beta$ , where  $\beta = 1$  for laminar flow and  $\beta = 2$  for turbulent flow, and a pressure volume work,  $p_1 / \rho$ , which the fluid needs to enter the system. The pump must raise the liquid and adds work  $W/w$  to the liquid. At the exit, the fluid has a potential energy  $gh_2$ , a kinetic energy  $\langle v_2 \rangle^2 / \beta$  and has a pressure volume work of  $p_2 / \rho$ . The Bernoulli equation is simply written then as

$$gh_1 + \frac{\langle v_1 \rangle^2}{\beta} + \frac{p_1}{\rho} + \frac{W}{w} - E_v = gh_2 + \frac{\langle v_2 \rangle^2}{\beta} + \frac{p_2}{\rho} \quad (11)$$

where  $E_v$  is a correction factor necessary for the equality.

In the study of transport phenomena, the starting point in the derivation is the local conservation statement for momentum or Newton's second law of motion for a fluid.

$$\rho \frac{Dv}{Dt} = \sum_i F_i = -\nabla \cdot \underline{\underline{\tau}} - \nabla p + \rho g \quad (12)$$

This statement says that on a unit volume basis, the mass times acceleration of a fluid particle is equal to the sum of the viscous forces, the pressure forces and the gravitational forces. Since mechanical energy is the product of a force and a displacement, this equation can be multiplied by the fluid velocity to obtain the local time rate of change of mechanical energy.

$$\rho \frac{D}{Dt} \left( \frac{1}{2} v^2 \right) = - \left[ \nabla \cdot p \underline{v} + \nabla \underline{\tau} : v + \rho v \cdot g \right] + p \nabla \cdot \underline{v} + \underline{\tau} : \nabla \underline{v} \quad (13)$$

The left hand term represents the accumulation of kinetic energy and the term in brackets on the right side represents products of forces and velocities and hence the rate of mechanical work done by pressure, viscous and gravity forces. In order to explain the last two terms, the equation of thermal energy must be examined.

$$\rho \frac{DU}{Dt} = - \nabla \cdot q - (p \nabla \cdot \underline{v} + \underline{\tau} : \nabla \underline{v}) \quad (14)$$

The term of the left represents the accumulation of internal energy and the first term on the right represents heat conduction. The last two terms in the internal energy equation also appear in the mechanical energy equation but with opposite signs. The term  $p \nabla \cdot \underline{v}$  represents compressibility effects and may be either positive or negative. The term  $(-\underline{\tau} : \nabla \underline{v})$ , for Newtonian fluids, is always positive which means that this term always causes a decrease in mechanical energy and an increase in thermal energy. This term then represents the irreversible degradation of mechanical energy into thermal energy.

In order to obtain the Bernoulli equation, the mechanical energy equation is integrated over an arbitrary volume consisting of three types of surfaces: inlet and exit surfaces, fixed surfaces and moving surfaces. The moving surfaces provide a means of adding or removing work from the system, the fixed surfaces represent the confines of the system and the inlet and exit surfaces allow mass to enter and leave the system. After integration, the result is dependent only upon the inlet and outlet con-

ditions and for an unsteady state system is

$$\frac{d}{dt} (K_{tot} + \Phi_{tot} + A_{tot}) = - \Delta \left[ \left( \frac{1}{2} \frac{\langle v^3 \rangle}{v} + \frac{\Phi}{w} + G \right) w \right] + W - E_v \quad (15)$$

where  $K_{tot}$ ,  $\Phi_{tot}$  and  $A_{tot}$ , are respectively, the total kinetic energy, potential energy and thermodynamic work content;  $W$  is the rate at which the surroundings perform mechanical work on the system; and  $E_v$  is the "friction loss." This term is given by

$$E_v = - \int_V (\underline{\tau} : \nabla \underline{v}) dV \quad (16)$$

and represents the irreversible conversion of mechanical energy to thermal energy.

For a steady-state liquid system, Equation 15 becomes

$$gh_1 + \frac{1}{2} \frac{\langle v_1^3 \rangle}{\langle v_1 \rangle} + \frac{p_1}{\rho} + \frac{W}{w} - \frac{E_v}{w} = gh_2 + \frac{1}{2} \frac{\langle v_2^3 \rangle}{\langle v_2 \rangle} + \frac{p_2}{\rho} \quad (17)$$

A comparison of this equation with Equation 11 indicates that

$$\beta = \frac{2 \langle v_1 \rangle^3}{\langle v_1^3 \rangle} \quad (18)$$

This derivation proceeds from a fundamental law to a general equation of engineering utility by logical and reasonable steps. The scope of the equation, its relation to fundamentals, and the lack of balancing "fudge factors" illustrates to the student the scientific basis of engineering and gives him confidence in the application of this equation and others of similar origin.

#### ACKNOWLEDGEMENT

Permission of the McGraw-Hill Book Company to quote and paraphrase passages from the introduction and first chapter of Badger and McCabe's "Elements of Chemical Engineering" and from the preface of Bennett and Myers' "Momentum, Heat, and Mass Transfer"; and of John Wiley & Sons to quote a passage from the preface of Bird, Stewart, and Lightfoot's "Transport Phenomena" is gratefully acknowledged.

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## NOMENCLATURE

Dimensions are given in terms of mass (M), length (L), time  $t$ , and temperature (T.) Vectors have a single underline and tensors have a double underline. Force is not considered a fundamental dimension, but is assigned instead the dimensions of mass-acceleration instead the dimensions of mass-acceleration product ( $ML/t^2$ ). This "absolute" system of dimensions is commonly used by physicists, much less commonly by engineers.

$A$	= thermodynamic work function, $ML^2/t^2$ .
$C_p$	= heat capacity at constant pressure per unit mass, $L^2/t^2T$ .
$D_{AB}$	= binary diffusivity for system of species A-B, $L^2t$ .
$d$	= molecular diameter, L.
$E_v$	= total rate of viscous dissipation of mechanical energy, $ML^2/t^3$ .
$G$	= Gibbs free-energy per unit mass, $ML^2/t^2$ .
$g$	= gravitational acceleration, $L/t^2$ .
$h_1, h_2$	= elevation, L.
$j_{A,y}$	= mass flux of species A in the y-direction, $M/tL^2$ .
$K$	= kinetic energy, $ML^2/t^2$ .
$K$	= Boltzmann constant, $ML^2/t^2T$ .
$k$	= thermal conductivity, $ML/t^3T$ .
$m$	= mass of molecule, M.
$p$	= fluid pressure, $M/Lt^2$ .
$q_y$	= y-component of the heat flux vector, $M/t^3$ .
$T$	= absolute temperature, T.
$t$	= time, t.
$u$	= mean molecular speed, $L/t$ .
$\underline{v}$	= mass average velocity, $L/t$ .
$\langle \underline{v} \rangle$	= space average value of velocity, $L/t$ .
$W$	= rate of doing work on system, $ML^2/t^3$ .
$w$	= mass flow rate, $M/t$ .
$\alpha$	= thermal diffusivity, $L^2/t$ .
$\beta$	= velocity function (defined in Equation 18), dimensionless.
$\mu$	= viscosity, $M/Lt$ .
$\nu$	= kinematic viscosity, $L^2/t$ .
$\rho$	= density, $M/L^3$ .
$\underline{\underline{\tau}}$	= shear stress tensor, $M/t^2L$ .
$\Phi$	= potential energy, $ML^2/t^2$ .

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averted the following spring. Jay's parents insisted that he bring his son home for a family inspection. Jay and Jayshee realized that a six-month old child from antiseptic America would have an extremely difficult time in India, possibly even dying of dysentery. They finally persuaded Jay's family to come to Wyoming instead.

Jay has moved steadily ahead with Sinclair. Shortly after his son was born, they asked him to move out to the company town of Sinclair so that he would be more readily available whenever technical difficulties arose. For \$50 per month, he rents a two-bedroom, one-floor company-owned house. At his present salary rate of \$700 per month, he has been able to live well and still help his family. Until his brother completed college last summer, he contributed \$100 per month towards his expenses. Financial help to his family in India has been accomplished with the aid of a favorable exchange rate which converts one dollar into four rupees.

This true story points to one way that the continued shortage of U.S. chemical engineers is being met. Not an isolated example by any means, Jay Saraiya is only one of sixteen non-citizen chemical engineers graduated and placed in permanent positions in the U.S. by one educational institution, Montana State University, in the past six years. The employers of these men include some of the U.S.'s leading companies at some of their most attractive locations. Just as nature abhors a vacuum, so good jobs are going to be filled whether or not American boys want them.



# Evaluation of an Approach to Plant Design

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Plant Design is taught at McMaster University in two courses. The theory and design of pieces of equipment are discussed as part of a four credit course called Economics and Technology. This is taught to fourth-year students for both the fall and spring terms for two hours a week. In addition to this course, three credits are given to a senior project laboratory: an 80-hour workshop in the spring term. This paper evaluates a novel approach to the project laboratory. The major novelty arose in (1) the student's responsibility, (2) the time allocation, (3) the staff supervision, (4) the outside judging committee, and (5) the problem specification. These are discussed, and the evaluation follows.

## Project Description

### *The Student's Responsibility:*

Each student decides how he is going to make the quantity of specification material, designs his own plant, submits a complete report, and verbally defends his approach and design before an outside committee.

### *Time Allocation:*

Eighty hours and only 80 hours are to be spent on this project. Each student draws up a time schedule for his calculations; then the students meet as a committee and draw up a work schedule that will be adhered to by each. The schedule breaks into a number of major stages. At the end of each of these, the students meet with the staff for an hour of constructive criticism about how each has handled the assignment.

The 80 hours are divided into a 12-hour/week design laboratory that simulates an industrial situation. A room is booked, a filing cabinet is placed at the student's disposal, and the design laboratory is not supervised; but the students are expected to be either in the booked room or in the library during the design laboratory time. We emphasize that they are not to work outside of class time.

Full marks are given for the most efficient use of the time the student allots himself for each calculation. Marks are deducted if he does not have each project finished on time; if he does a five-minute calculation for a three-hour period or if he spends time doing unimportant and unrelated calculations, he loses marks.

The marking scheme for each criticism session is based on a total of 10 marks for every hour of design laboratory that has elapsed since the last criticism session.

### *The Staff Supervision:*

1. Give constructive criticism after each major

design effort. While each completed project is fresh in the student's mind we explain how he could have saved himself time, and suggest reliable short cuts and good design technique. The staff members with the most experience in the given field criticize the effort.

2. Are prepared to present request-lectures *before* each major design effort. Any staff member will present a maximum of a one-hour workshop or discussion session provided such a workshop is requested by the students at least two days in advance of the lecture time and provided that hour is the first hour of the allocated project for the topic under consideration.

The staff are not consulted otherwise. All the staff are involved in this project.

### *The Outside Judging Committee:*

The students design their plant for three outside judges, and not for the staff members.

To the judges we suggest a complicated marking scheme for the oral presentation. (The four page, typed report from each student that is given to the judges provides background information for the judges. We feel that it is too burdensome to ask them to mark the written reports). After each presentation, the judges are given as much time as they want to finish evaluating one speaker before the next starts.

### *The Problem Specification:*

Little information is provided in the specification. The quantity and quality of a given product and the utilities available—these alone are given. Table I is a typical specification.

The students are informed also of the emphasis expected and the report specifications.

All calculations are to include assumptions and limitations and estimated accuracy for each answer. The calculations must be legible and easy to follow.

Specifications are required for each major piece of equipment. For heat exchangers, a standard 1-in. nominal tube is stipulated and details required include approximate tube count, tube length, and pitch; shell diameter; baffle spacing; pipe connections; material of construction; working pressure; and mounting instructions. A detailed calculation for the selection of one pump is needed. The types of control required must be indicated but not specified. The mechanical design of the reactor and of one of the major pieces of separation equipment is to be included.

The production and the capital investment costs are to be calculated.

### *The report:*

The design report must be turned in one week before the presentation day and later is filed in

TABLE I. DESIGN PROJECT SPECIFICATION

Desired: A plant to produce

50 long tons/24 hr. of 95% pure monomeric  
styrene

or

300 long tons/24 hr. of 95% pure monomeric  
styrene

Utilities available:

Fuel oil

Natural gas

Electricity

Cooling water: Lake water 5°C. (winter) and  
20°C. (summer)

City water (same average  
temperature)

Steam: 200 psig, 100 psig, and 50 psig  
(all saturated)

the chemical engineering department library. The report consists of two parts: the body and the appendix.

The body is a four- to five-page, double-spaced, typed summary report of what was done, why it was done, how it was done, and what conclusions were drawn from the calculations. The purpose of the report is to convince the outside committee that the best possible design has been turned out in the time available. The readers are the outside committee, a group with chemical engineering training who may or may not be familiar with the subtleties of the design topic. Four copies of the body of the report are required.

The appendix of the report is a well-indexed collection of all of the actual calculations done, together with appropriate summary pages interspersed throughout the work. The calculations need not be typed; but they must be legible and indicate the calculation approach. The purpose of the appendix is to supply a complete record of all of the calculations done on the design project so that anyone who had to do a more elaborate design can go one from where each student stopped rather than be forced to recalculate work that has been done. The average reader of the appendix will have a chemical engineering background, will probably know nothing about the design topic, and will be interested in learning what has been done and what are the limitations

and assumptions involved in the calculations.

#### Evaluation

The advantages and the weaknesses of this approach to design teaching are outlined as follows.

#### Advantages

We have found the following advantages:

1. The outside committee adds reality to the project for the students. The students' emphasis is shifted so that they are working against the outside committee and its evaluation, rather than against a staff member for a grade. The students feel their reputations are at stake. Twenty percent of the final class mark depends on the outside committee's judgment. Our outside committee members not only have been very learned in the field but have asked stimulating and probing questions. The committee for the styrene project included a senior process designer from Dow Chemical (who produce styrene), a senior chemist in the petrochemicals division from Polymer Corporation (who also make styrene), and a University of Toronto colleague who ran the plant project design there.
2. The students enjoy the individual responsibility. Since we do not form companies, each student has to do his own creative design and

justify it on the basis of economics.

3. The students enjoy the diversity of responsibility, including choice of process, design, and cost estimation. They say they prefer to make an overall, high-spot design of a complete process rather than a detailed design of an element of a process.

Twelve hours of design laboratory time are free between the time the students hand in their reports and the oral presentations. We use this time to build a scale model of one student's plant. For the degree of accuracy required, we found that this could be done for a styrene plant for about \$10. The scale was  $\frac{1}{4}$  in = 1 ft.

4. Lectures are given only at the students' request. Most want to get on with the job; few lectures are required. This pleases the students and the staff alike because we feel that they are asking and answering their own questions.
5. The criticism periods after each major design effort give rapid feed-back of suggested improvements and the type of assumptions to make. Since any lectures are at the request of the students, we want strong feed-back on their approach as they proceed.
6. The limitation for the time spent on this project is worthwhile. The students do not jeopardize their standing in other courses by devoting excessive extra time to this course; they learn to match their designs to the time available. The marking scheme for the criticism sessions accentuates matching time with accuracy.
7. The marking scheme specified to the judges requires about 10 minutes per speaker. Although the judges think the marking scheme cumbersome, we find it very helpful to the students.
8. It is easy to rate each student.
9. Staff load for the course is distributed among the staff members. Furthermore, the students gain from the background experience of staff specialists in the criticism periods.

#### Weaknesses

Some weaknesses of this approach are:

1. An apparent lack of understanding of the role of plant design in an economics analysis. The students do not seem to realize that the preliminary plant design is done to improve their accuracy in their economic assessment of the process. We think that the onus of this is not upon the design course but rather on the economics and technology course which one of us also taught. In the future we plan to be more specific in the students' purpose in doing the plant design.
2. Inadequacy of decision-making theory. The students do not fully appreciate the consequences of the various decisions made. More emphasis will be given to this topic in the economics and technology courses in the future. For example, not only will we creatively look at process flow sheets as we do

now, but we will do exercises on getting quick numbers for equipment cost for several different flow-sheets. This training in cursory equipment costing should help them to allocate their design time for any preliminary design project itself.

3. Inadequacy of the criticism sessions. Whether the improvement is achieved by converting the sessions into a verbal presentation to the combined staff after each sub-project or by supplying more staff manpower to correct and criticize individual efforts, the whole key is the constructive criticism of the student's effort at various stages along the way immediately after he has completed his work.
4. Poor distribution of staff responsibility. The staff coordinators sometimes do not call on other staff members to help out enough.
5. Paucity of time available for the design. The completeness of the project could be improved either by requiring the students to do some work outside the specified hours, by forming companies of design engineers, or by reducing the scope of the project. Increasing the student's homework is easy to justify because our fourth year, second term load is relatively light. The formation of companies requires careful consideration. The advantages for individual design that both the staff and the students have appreciated are
  - (a) each student is completely responsible for all of the decisions and calculations.
  - (b) each sees all facets of the design rather than working on his specialty with figures that are handed to him by someone else.
  - (c) each realizes that the individual mark can be given at the end of the project.

It would be interesting to see if we can incorporate all of these advantages by forming companies of two students and by insisting that each student be able to defend any part of the final design. The suggestion of reducing the scope of the project has received a negative reaction by the students.

6. Poor technical communication. Although the general reaction to the student's oral presentation has been favorable, the written reports are poor. We have introduced a two-credit course in technical communication into our second-year program in an attempt to remedy the situation.

#### Summary

A novel approach to teaching plant design is being developed at McMaster University. The uniqueness of this approach lies in the method of handling the student's responsibility, the time allocation, the staff supervision, the judging committee, and the problem specification.

An evaluation of the approach, based on its application to one project with a class of fourth-year students, shows that it has many advantages and several weaknesses. With the correction of the latter, the approach should offer great promise as a powerful method of teaching design.

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